CIVIL INFRASTRUCTURE

ADVANCED SENSING TECHNOLOGIES AND ADVANCED REPAIR MATERIALS FOR THE INFRASTRUCTURE: WATER SYSTEMS, DAMS, LEVEES, BRIDGES, ROADS, AND HIGHWAYS

Technology Innovation Program
National Institute of Standards and Technology
Gaithersburg, MD 20899
March 2009

The Technology Innovation Program (TIP)[1] at the National Institute of Standards and Technology (NIST) was established for the purpose of assisting U.S. businesses and institutions of higher education or other organizations, such as national laboratories and nonprofit research institutions, to support, promote, and accelerate innovation in the United States through high-risk, high-reward research in areas of Critical National Need (CNN). Areas of Critical National Need are those areas that justify government attention because the magnitude of the problem is large and societal challenges that can be overcome with technology are not being sufficiently addressed.

TIP seeks to support accelerating high-risk, transformative research targeted to address key societal challenges. Funding selections will be merit-based, and may be provided to industry (small and medium-sized businesses), universities, and consortia. The primary mechanism for this support is cost-shared cooperative agreements awarded on the basis of merit competitions.

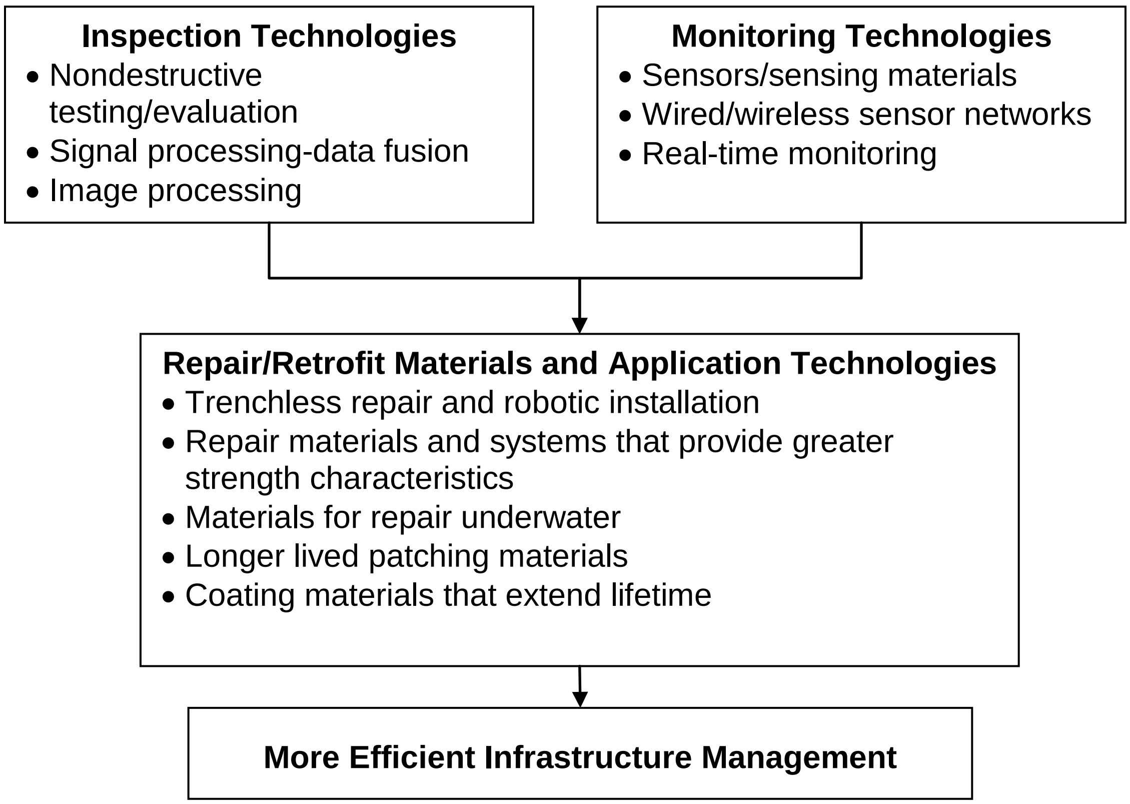
AN AREA OF CRITICAL NATIONAL NEED

The proposed topic: "Advanced Sensing Technologies and Advanced Repair Materials for the Infrastructure: Water Systems, Dams, Levees, Bridges, Roads and Highways" is within the Critical National Need area of civil infrastructure. This topic was selected from a larger set of challenges in civil infrastructure where transformative research could be expected to have large societal impact. Input regarding potential challenges in civil infrastructure was obtained from government agencies and advisory bodies (such as the National Research Council, the National Academy of Sciences, the National Academy of Engineering and the Institute of Medicine), the Science and Technology Policy Institute (STPI), industry organizations, leading researchers from academic institutions, and others. This process led to the selection of “Advanced Sensing Technologies for The Infrastructure: Roads, Highways, Bridges and Water Systems” for the inaugural FY 2008 TIP competition. The presently proposed area expands upon the scope of the FY 2008 TIP competition in continued support of our nation's civil infrastructure.

The objective of the FY 2008 - selected projects is to advance the state-of-the-art of sensing technologies that will make automatic sensing of the structural integrities and/or deterioration processes of bridges, roads, water mains, and wastewater collection systems more accurate, easier to use, and more economically feasible. Inspection and monitoring make up one component of infrastructure management. The need for better tools for infrastructure management is national because every municipality and state in the nation faces infrastructure management challenges. The need is critical because portions of infrastructure are reaching the end of their life-spans and there are few cost-effective means to monitor infrastructure integrity and to prioritize and effect the repair or retrofit of infrastructure elements.

Transformational research is required to overcome these challenges in civil infrastructure. Incremental improvements of current technologies will not meet the challenges of providing cost-effective, widely-deployable solutions to the problems of infrastructure management.

Sensing technologies are one aspect of infrastructure management. Automated sensing provides information that helps to lead to an infrastructure management decision to repair an infrastructure element, as depicted in the figure.



Infrastructure management requires that once a structural defect is detected, that an economical repair be made. Advancing the technologies of repairing infrastructure elements in contact with the water, salts (road salt or marine environments), and subjected to thermal changes requires transformative research to significantly extend the lifetimes of repairs, lower the costs of repairs, and provide repair technologies that are suitable for a wide range of conditions. In the remainder of this document "retrofit" refers to fitting into or onto a structure that is currently in service or that could be returned to service with repairs. A retrofit material or application can be one that returns the infrastructure element to original specifications or that improves the element beyond the specifications of the original construction. Advanced materials for new construction applications, rather than for repair or retrofit, although important, are not included in this topic area.

Several types of civil infrastructure elements contain some portion of their structure below a water surface. Examples of underwater infrastructure elements include piers and abutments that support bridges, as well as navigation locks, dams, and levees. These types of structural elements in aquatic environments provide significant challenges for inspection and repair.

MAGNITUDE OF THE PROBLEM

Civil infrastructure—the framework of interdependent networks and systems required to provide services and support social and economic activities—comprises transportation systems (e.g., highways, roads, rail systems, ports), utilities (e.g., water, power, communications), and public facilities (e.g., schools, recreation, prisons, postal facilities). As the economy grows, we become even more dependent upon larger and more complex networks of civil infrastructure that require ever increasing expenditures to maintain their safety and security. Each year Federal, state, and local governments spend billions of dollars to upgrade and repair transportation systems and water resources.

Public (Federal and state) expenditures on infrastructure have grown by 1.7% per year from 1956 to 2004 and in recent years, have been growing even more rapidly, rising by 2.1% per year, after adjustment for inflation.[2] This rate of growth translates into a constant fraction of GDP, about 1% to 1.2%, being spent on infrastructure. The Congressional Budget Office reported that Federal and state governments spent $67 billion on highway infrastructure and $28 billion on drinking water and wastewater infrastructure in 2004.

Despite these large expenditures the nation continues to suffer staggering consequences from infrastructural decay. The August 2007 collapse of the I-35W bridge in Minneapolis, Minnesota cost 13 lives and will cause economic losses to the city's economy that are estimated to be close to $200 million. The Environmental Protection Agency (EPA) reported that there are 240,000 water main breaks per year in the United States. Baltimore, Maryland, as an example of an older urban area, suffered almost 1200 water main breaks in 2003.[3] In addition, it is reported that the Washington Suburban Sanitary Commission, which manages a pipe system about twice the length of the U.S.-Mexico border, in suburban Washington, D.C., recorded 2,129 pipe breaks in 2007 and more recently witnessed a massive water main break that required fast water rescue from vehicles caught in the water rushing from the water main break.[4] Leakages and breaks in water distribution systems are estimated to waste up to 6 billion gallons of drinking water each day.[5]

Damaged infrastructure also directly impacts large numbers of Americans. The American Society of Civil Engineers estimates that Americans spend $54 billion each year in vehicle repairs caused by poor road conditions. Drops in water system pressure, resulting from water main breaks, lead to microbial contamination of drinking water. Each day, one can find news reports that a half-dozen or more communities are affected by "boil water" alerts due to water main breaks or other failures within their water-delivery system.

A lack of predictability of infrastructure failures is understandable. All engineered structures, including the entire nation's civil infrastructure, have elements with variable life-spans. Structures approach the end of their life spans through a complex process that involves long-term environmental degradation, wear, and episodic events like impact or fire. All engineered structures must be maintained, including periodic repair and/or retrofit, in order to reach and extend their usable life spans. Because the factors that affect the integrity of engineered structures cannot be perfectly predicted, the process of the degradation of the integrity of the structure must be sensed in some form. Today, the most common form of assessing the integrity of a structure is visual inspection. The visual inspection provides a qualitative assessment of damage caused by the various degradation processes that affect the particular structure. Visual inspection is sometimes supplemented with other non-quantitative methods like judging the sounds produced by dragging chains or hammering to detect delamination of structural surfaces.

Technology that could provide more quantitative data on integrity and condition of infrastructural elements is currently very expensive and is able to provide only a partial picture that is specific to the type of technology used. More advanced inspection systems involve ground-penetrating radars, sound-wave propagation methods, electrical impedance measurement, and other methods that can detect the presence of some subsurface defects. These methods are costly, requiring expensive equipment, significant amounts of skilled operator labor for setup, measurement and interpretation, and, in some cases, removal of layers of bridge decking or road surface, in the case of roadways or removal of water in the case of pipe systems and components of navigable river structures. For example, ground-penetrating radar provides very detailed quantitative data on the integrity of examined subsurface elements like the condition of reinforcing bar embedded in concrete. However, the cost of these surveys is so prohibitive that they cannot be used routinely. For example, a quantitative ground-penetrating radar study on the I-35W bridge in Minneapolis was estimated in 2006 to cost $40,000.

The amount of infrastructure to inspect is enormous. The nation has 1,000,000 miles of water mains, 600,000 bridges, and 4,000,000 miles of public roadway. Public safety professionals and engineers responsible for this infrastructure strive to maintain these systems. They seek to prioritize repair schedules and to avoid premature replacement of infrastructure. Better technologies have the potential to provide invaluable input to these recommendations by making the monitoring of processes and conditions that affect structures more quantitative, more thorough, and more frequent. Technologies that achieve the goal of continuous monitoring of structural integrity with costs low enough to permit wide-scale, permanent deployment, require transformative research.

Once inspection determines a defective or deteriorating element of infrastructure, the manager is faced with a decision to repair, retrofit, or replace the compromised element. This decision incorporates cost and longevity of repair/retrofit vs. the cost of replacement. Many state-of-the-practice repair technologies serve to ameliorate the problem for the short-term but do not provide long-term solutions. Some repair technologies require taking the infrastructure element out of service for some length of time, the length of time being a direct consequence of the repair technology. The technologies that offer longer-term repair or retrofit solutions often provide an initial cost for deployment that appears prohibitive when faced with a massive list of repairs to be effected. The result of present repair technologies is that they do not greatly extend the timeframe before very expensive complete structural replacement becomes a necessity. Transformative research is required to create repair/retrofit technologies that drastically extend operational times and to greatly prolong the usable life of infrastructure elements.

MAPPING TO NATIONAL OBJECTIVES

The focus upon improving the tools available for infrastructure managers to better maintain and preserve civil infrastructure elements maps well upon national objectives, Congressional testimony, and NIST's core competencies.

The National Academy of Engineering has identified the restoration and improvement of urban infrastructure as one of their fourteen grand challenges in engineering.[6]

Mark Funkhouser, Mayor of Kansas City, Missouri, appeared with mayors of other municipalities and testified before Congress on the problems their communities face with infrastructure maintenance and decay. He testified, "We're having a quiet collapse of prosperity." (June 12, 2008). Congressional committees are focusing more attention on the needs to secure, maintain, and improve critical infrastructure.

The national objective of infrastructure management as a priority has been with us for some time. The current administration has placed infrastructure investment at the forefront of its economic initiatives.

Sensing technologies and materials science correspond directly to NIST's areas of technical competence. NIST conducts research that affects the development of building codes and standards and that leads to new tools for evaluating seismic strength of new and existing buildings and communities. In addition, the U.S. Measurement System (USMS) at NIST[7] also includes the measurement need of developing new and innovative sensor technologies for in-line, real-time, and continuous monitoring in buildings and construction sites.

MEETING TIMELY NEEDS NOT MET BY OTHERS

Overview

Water, wastewater, and highway infrastructure have been identified by groups of independent experts, e.g. the National Academy of Engineering[6] as challenge areas within the Critical National Need of civil infrastructure. There are other agencies that are working on problems associated with these infrastructure areas. Four Federal agencies were identified that operate twelve programs that might have shared commonalities with TIP's identified Critical National Need. Examination revealed that none of these programs has the scope and size that should result from a funding commitment from TIP to support innovative early stage research in these challenge areas of civil infrastructure.

TIP's Role

In general, local and state governments have significant knowledge gaps regarding quantitative assessment of infrastructure integrity, yet they do not have the funds and ability to develop more cost-effective advanced sensing tools that would eliminate the knowledge gaps or to develop advanced materials and application technologies that would provide long-lived repair of defective or deteriorating structures. One Federal research program targets advanced sensing for infrastructure – the National Science Foundation's "Sensor Innovation and Systems Program." Total funding for this program is $5 million per annum and innovation in sensing is only one of several categories of research supported under this program. Other programs were identified in which new sensing technologies might be funded, but none of the programs is targeted specifically at new or early stage sensing technologies. The civil infrastructure grants that are provided by the National Science Foundation (NSF) are primarily targeted for academic fundamental research and are smaller than those of TIP. The Exploratory Advanced Research Program of the Federal Highway Administration (FHWA/USDOT) is currently targeted at Intelligent Transportation projects. The Remote Sensing and Spatial Information Program of the Research and Innovation Technology Administration (RITA/USDOT) is a university-focused program that asks applications to use existing technologies in a transportation context.

SOCIETAL CHALLENGES

Societal challenges are defined as problems or issues confronted by society that when not addressed could negatively affect the overall function and quality of life of the nation, and as such justify government attention. The societal challenges that TIP is addressing are the absence of cost-effective means for 1) establishing accurate assessments of the integrity and condition of civil infrastructure elements, and 2) providing long-lived repairs to deteriorating infrastructure. Continued challenges to prioritize infrastructure projects negatively impact the safety and economic well-being of the nation. The challenge of providing accurate assessments and/or measurements of infrastructure quality, and then reinstating or improving performance, is large due to the fact that engineered structures are complex, consisting of many materials and having many types of degradation processes and modes of failure, all of which must be addressed. Two elements of this societal challenge are inspection and monitoring issues, and advanced material and repair issues.

Repair/retrofit materials and the methods to apply the material can be considered a system. A transformationally better material is not useful if there is not a method to cost-effectively deploy the novel material in real-life repair/retrofit applications. New materials predominantly for repair could have manufacturing technology needs, but could also need application approaches for deployment. For example: novel material application system technologies could include the methods to produce the novel repair/retrofit material at the repair site.

These two elements, inspection/monitoring and repair/retrofit systems, were selected from a much larger set of challenges in civil infrastructure including smart structures, green and sustainable infrastructure, novel materials for new construction, etc.

The societal challenges are discussed in the context of two key application areas: 1) water and wastewater collection mains; submersed infrastructure elements; and 2) bridges, roads, and highways.

Water Mains and Wastewater Collection Systems; Submersed Infrastructure

Structures that contain water (water mains and wastewater collection systems) or that are submersed in water (dams, levees, navigation locks, bridge piers, etc.) are especially challenging for inspection, monitoring, and repair. Water delivery mains and wastewater collection mains are buried, often underneath other construction in the form of roadways or buildings. The burial of these systems makes external visual inspection impossible without digging trenches along the water systems. The expense of trenching is large, not just from the trenching itself, but also from the necessary repair of surface structures damaged during the trenching. Submersed structures can have high velocity water around the structure, as for dam gates or bridge piers. Inspection devices for deeply submersed structures are subjected to significant external hydrostatic pressures. Repair of buried infrastructure or of submersed infrastructure is also particularly challenging because water often interferes with placing and the setting or curing of repair/retrofit materials.

Inspection and Monitoring Issues for Water and Wastewater Mains, and Submersed Infrastructure

Visual inspection of the interiors of installed water mains and wastewater pipe can be accomplished by dragging pipeline inspection gauges (“pigs”) with cameras, eddy-current monitors, or an aid that provides an image for the inspector. Water mains provide an especially great challenge for inspection and monitoring technologies. There is a large variety of types of piping that have been used for water mains and these different pipe constructions have different degradation processes. Inspection and monitoring methods that work with one type of water main pipe (e.g. unlined iron), may not work with another (e.g., asbestos-cement). Water main inspections are often limited for different reasons. For example, water mains must be drained for some of the inspection technologies, and “pigs” dragged through undrained mains can disturb deposits within the mains which must then be flushed from them to prevent consumer complaints. Pigs can also potentially dislodge materials that are preventing leaks and leave problems in their wake. In 2007, the EPA’s Office of Research and Development reported with regard to condition assessment of water delivery infrastructure that “the technical and/or economic feasibility of measuring the right parameters, and/or the ability to interpret the data, are not adequate for high-risk mains.”[8] With regard to wastewater pipe inspection methods, the EPA concluded “As the focus of condition assessment continues to broaden to include targets beyond the reduction of excessive hydraulic loading due to (infiltration and inflow), sewer system inspection technologies and investigation approaches must evolve.”[8]

Primary inspection of underwater portions of structures is usually by manual visual means. Engineer-divers inspect the structure visually, and in cases where visibility is extraordinarily low, tactilely. Some effort at developing remotely controlled inspection vehicles has been made; however, due to various technical details, such as maintaining position in fast currents, technologies that determine condition below the visual surface of the structure, and high cost, these remote vehicles are not widely accepted as substitutes for divers.

Monitoring the condition and usage of infrastructure is also fundamental to its maintenance. Municipal utilities are not able to monitor the extent of leakages in their distribution systems. They know how much water they treat and they know how much water passes through customer water meters. The difference between those two quantities comprises leakages and unmetered uses, the latter of which includes, among others, firefighting and local government usages including irrigation of public land. Leakage rates vary across municipalities depending on the age and quality of the infrastructure. Nationwide, drinking water loss is estimated at six billion gallons per day or approximately 15 percent of the water sanitized and treated for use. Water loss due to system leakages is not just lost water, it is also the loss of the treatment chemicals and the energy required to pump six billion gallons of water through the water delivery systems every day. Water leakages also create other infrastructural damage. They undermine structural and roadbed foundations, and they disrupt power grids and telecommunications that are in underground proximity to water mains.

Scour is the most frequent cause of bridge collapse and also impacts levees, navigable lock structures, and other underwater structures. Scour often depends on episodic events connected with rapid water flows associated with flooding, either periodic flooding from seasonal flow melts, or non-periodic flooding associated with stormwater. The episodic nature of much scour damage points to the benefits of a monitoring solution over infrequent periodic inspections. Long-lived, economical, scour monitoring systems must contend with debris impacts as well as with high water velocities.

Repair/Retrofit Material and Application Technology Issues

Water and wastewater piping systems are buried and burial provides added difficulties for repair as well as for structural integrity sensing. In general there are two ways of repairing or renovating existing water and wastewater pipes. One is to excavate and replace the pipes. The other is a group of technologies that are trenchless in that they do not require excavation. Trenchless technologies include various sliplining techniques and also devices that clean and spray a lining material on the inside of pipes after removal of water from the pipes. These technologies, while reducing the burdens caused by excavation, have limitations that limit their range of deployment. As one example, plastic lining material can be installed in water mains. These flexible liners are fed into the main and are either pressed or adhered to the internal wall of the main being repaired or have a shape-memory characteristic that allows expansion to the outer wall of the main. These liners provide good results in preventing small leaks in water mains and in providing a cleaner internal surface on straight runs of pipe. However, junctions of mains and smaller diameter pipes in residential communities present challenges to these technologies. New technologies based on robotic joining of liner segments at junctions could be beneficial as would technologies for both smaller pipes of residential areas and very large diameter mains. Spraying of mortar-cement on the inside annulus of unlined iron pipe may have a tendency to be site specific, limiting this technology also.

Bridges, Roads, and Highways

Inspection, monitoring, and repair of roadways and bridges are more accessible than is the case for water systems. However, the nature of their cyclical loading and their exposure to more extreme environmental conditions necessitates more frequent inspection and repair cycles. The current state-of-the-practice for routine establishment of the integrity of bridges and roads is typically a visual inspection, augmented with some physical aids like the sounds made by chains dragged across a road surface. Current repair practices for road and bridges comprise patch-like repairs until large-scale renovations, e.g. deck replacement, can be effected.

Inspection and Monitoring Issues

Technology applied to surface infrastructure inspection is limited, existing as aids to the human-based inspection. Visual inspections, used since the first builders, especially when coupled with chain-dragging, hammer soundings, and the removal of core samples, are time-consuming and require skilled operators, making them expensive. In addition to the expense, the finite supply of skilled inspectors/engineers necessarily limits the frequency of inspection. As a result it is typical for bridges to be inspected perhaps every other year and for deficient bridges to be inspected once a year. Beyond the infrequency of inspection, these types of personnel-intensive inspections are, by their nature, subjective. The insufficiency of current infrastructure condition and quality assessment practices has been studied and reported. In the most recent study of principal bridge inspection methods (the NBIS[a]), FHWA concluded that the condition ratings that the NBIS generates are subjective, highly variable, and not sufficiently reliable for optimal bridge management.[9] The FHWA also reported that in-depth inspection, assigned for deficient bridges, might “not yield any findings beyond those that could be noted during a routine inspection.”[10] Monitoring issues also affect the highway infrastructure. Bridge and road surfaces

[a] The National Bridge Inspection Standards is used by bridge inspectors in state departments of transportation. Many states expand upon the NBIS.

are designed to accommodate a particular level of loading. Excessive loading puts a structure at risk in two ways. The first is catastrophic failure of the structure when its maximum load and safety factor have been exceeded. The second risk comes from fatigue.[a] Fatigue arises from load-cycling over very long periods of time. Fatigue develops microscopically, weakening structural elements over time, resulting eventually in catastrophic failure of an element. There are insufficient cost-effective means for monitoring the load history of infrastructural elements or of monitoring continuously and cost-effectively the fatigue state of the individual elements. In prepared testimony (2007) before the United States House of Representatives, Committee on Transportation and Infrastructure, Mr. King Gee, Associate Administrator for Infrastructure (FHWA), and Mr. Gary Henderson, Director, Office of Infrastructure Research and Development (FHWA) stated, “Monitoring systems that are available today require routine maintenance and repair and continuous assessment to ensure that they are working correctly. In addition, they do not eliminate the need for regular visual inspections.”[10]

Repair/Retrofit Material and Application Technology Issues

Long-lived repair of road surfaces, bridge structures, and sub-surface piers and abutments are also limited by existing material technologies. Current asphalt and asphalt repair materials are highly susceptible to freeze-thaw damage occurring due to water penetration into and around asphalt repairs. Pothole repairs with state-of-the-practice materials often last less than a year, requiring routine repatching of surfaces until the entire surface is replaced. Although longer life-time materials might be available, their initial cost can persuade infrastructure managers to repair more sites with the short-lifetime materials. Another example of a challenge posed by current infrastructure repair materials is the vulnerability of current reinforced concrete to corrosion of the metal used for the reinforcing. Non-metal, composite-based reinforcing bar could potentially extend the lifetime of deck and roadway replacements by avoiding the susceptibility of corrosion if suitable bonding to current or novel cementitious materials could be achieved.

Summary

The societal challenges—needed improvements in cost-effective inspection and monitoring of critical infrastructure systems, and transformational improvements in materials and technologies for application of these materials, particularly those for application to water delivery systems, wastewater mains, dams, levees, bridges, and roadways—can potentially be resolved with better and more cost-effective technologies. Real-time data on the structural integrity of infrastructure components is not only useful for determination of repair and retrofit scheduling, but also for emergency notification in the event of impending catastrophic failure. There are currently no cost-effective, field-deployable sensing systems that are capable of providing continuous data with which to prioritize repair and retrofit schedules and that provide sufficient warning of impending catastrophic failure. There has been progress in the development of embedded sensors for new construction; however, these systems are not deployable to existing components of the infrastructure. It is clear that both the EPA and the FHWA concur that current infrastructure inspection and monitoring systems are inadequate and that better infrastructure sensing systems, based on current state of the art technologies, are either not

[a] Fatigue is a material degradation that occurs when the loading-unloading cycle occurs many times with loads beyond a certain amount. Fatigue begins as microscopic cracks that weaken the material’s strength properties. The cracks often grow until the material fails.

available or not economically feasible. An analysis of the gap between these societal challenges and the investment in solutions to these challenges found insufficient funding of truly transformative research, as opposed to research directed at making incremental improvements, in the areas of materials and processes for repair of infrastructure elements.

New sensing technologies that produce real-time (time-effective) monitoring data, and that can also help or aid in the interpretation of the acquired data, therefore will enhance the safety of the public by issuing timely and accurate alert data on structural integrity. New sensing technologies will also allow more informed management of infrastructural investments by avoiding premature replacement of infrastructure and identifying those structures in need of immediate action. New repair/retrofit materials and means to implement material solutions will complete the infrastructure manager's toolkit to address more effectively the challenges presented by aging infrastructure.

TIP has decided to invest again in "Advanced Sensing Technologies and Advanced Materials for the Infrastructure: Water Systems, Dams, Levees, Bridges, Roads and Highways." Within the Critical National Need of civil infrastructure, these new technologies will provide increased lifetimes, security and safety of elements of critical infrastructure. The vision for this funding opportunity is:

- To develop new tools and techniques that will enable infrastructure managers to monitor the structural health of critical national infrastructure elements that are essential for the health of the nation, its economy, and its citizens;
- To develop the means to sense the safety, security, and integrity of engineered structures above ground, in ground, and below water surfaces, that are within the nation’s highway, water, wastewater, and water control systems that provide that information to managers of these systems in a time-and-need effective manner; and
- To develop novel advanced materials and/or novel application technologies that will make more economical repairs or retrofits and extend the usable lifetime of existing civil infrastructure.

Those seeking further information should consult the Federal Funding Opportunity notice.

References

1. "Technology Innovation Program," America COMPETES Act, P.L. 110-69, Sec. 3012, signed on August 9, 2007.

2. "Issues and Options in Infrastructure Investment," Congressional Budget Office, May 2008.

3. http://www.epa.gov/awi/distributionsys.html

4. Washington Post: Under Pressure, p. A16, June 17, 2008; Washington Post: Water Main Break Forces Dramatic Rescue of Nine, p. A01, December 24, 2008.

5. "Developments in Water Loss Control Policy and Regulation in the United States" G. Kunkel, Leakage 2005 – Conference Proceedings. (Data on national drinking water loss depends on the 1998 USGS Circular 1200 that identified "public use and loss." The USGS does not have the capability to separate the real loss from the apparent loss of unmetered public uses like firefighting. The statistic, however approximate, is supported by data from the Survey of State Agency Water Loss Reporting Practices, Beecher Policy Research, 2002.)

6. "Introduction to the Grand Challenges for Engineering," National Academy of Engineering, February 2008.

7. http://usms.nist.gov/usms07/index.html

8. "Innovation and Research for Water Infrastructure for the 21st Century Research Plan," U.S. Environmental Protection Agency, April 2007.

9. "Reliability of Visual Bridge Inspection," Turner-Fairbank Highway Research Center, Federal Highway Administration, March 2001. http://www.tfhrc.gov/pubrds/marapr01/bridge.htm

10. http://testimony.ost.dot.gov/test/pasttest/07test/gee1.htm